LA-UR -80-2344

TITLE: DC ARC INTERRUPTION IN PRESSURIZED GASES

AUTHOR(S): P(ritindra) Chowdhuri

SUBMITTED TO: 1981 IEEE Power Engineering Society Winter Meeting, Atlanta, Ga., February 1981

DISCLAIMER

MASTER

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

Form No. 836 R2
St. No. 2629
1/78

DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

DC ARC INTERRUPTION IN PRESSURIZED GASES

P. Chowdhuri, Senior Member IEEE
Los Alamos Scientific Laboratory*
Los Alamos, NM 87545

SUMMARY

Low-voltage (1000 V and below) dc circuit interruption is of vital importance to many industries, such as transportation, chemical, etc., especially because of the increasing application of power semiconductor devices. The main areas of interest in the technology of low-voltage dc circuit interruption are:

(1) short interruption time
(2) minimum contact erosion

Short interruption time is required to protect the overcurrent-sensitive devices. Contact erosion has always been a serious maintenance problem for dc contactors.

A review of literature showed that most of the previous studies on low-voltage dc arc interruption were made with plain electrodes to understand the basic performance of the various gases. It was thought that the arc runners, the blowout coils and the arc chutes will be essential for low-voltage dc circuit breakers and contactors. Therefore, it would be appropriate to enclose the entire circuit breaker or contactor in atmospheres of various gases to assess its interrupting capability.

Tests were conducted on a 100-A, 600-V dc contactor with arc chute. The total volume of the contactor is about 8495 cm^3 (0.3 ft^3). The contactor was enclosed inside a 0.15-m^3 (5.4-ft^3) steel cylindrical tank of 686-mm (27-inch) length and 533-mm (21-inch) internal diameter.

It was found that the contact sticking problem was particularly severe with plain copper contacts. It also appeared that the contact sticking problem was minimized when the moving contact was the positive electrode. All tests described in this paper were performed with copper contacts brazed with silver contact plates, the whole assembly being silver dipped, and with the moving contact connected to the positive side of the source voltage.

Tests were started at 200 V dc, continued in steps to higher voltages and finished at about 1350 V with a constant resistive load of about 0.5 ohm and about 61 m (200 ft) of connecting cables.

Tests were performed in five gases — argon dry air, nitrogen, helium and hydrogen, each at four pressures — 0.17, 0.34, 0.52 and 0.69 MPa (25, 50, 75 and 100 psig).

Generally, three interruptions were made at each voltage level. The contacts were changed after each series of test. The main body of the contactor and the arc chute were changed only when the gas was changed. For instance, the same main body and the arc chute of the test contactor were used for all tests in hydrogen, but the contacts were changed after each series of test at a constant pressure.

The test contactors never failed to interrupt the power. The tests were usually terminated when the highest allowable voltage of the dc machines was reached or the arcing time was too long or if the safety valve of the pressure chamber opened because of excessive pressure build up.

The summary of the test results at 0.17 MPa (25 psig) is shown in Fig. 1. Average arcing times are plotted against interrupting power on semilog papers to facilitate comparison of performance among the five gases.

The performance of the various gases was qualitatively assessed by studying their physical and thermodynamic properties, and compared with the test results.

It was concluded that:

(1) For the test conditions: (a) the average arcing times in helium and hydrogen are the shortest and that in argon the longest; (b) contact erosion in hydrogen is the worst and that in argon the least; and (c) the static pressure in the chamber does not appear to have much effect on the arc interruption phenomenon.

(2) For relatively low-power and slow-speed interruptions, such as contactors, argon would be the best medium because it produces the least contact erosion. For high-power and high-speed interruptions, such as circuit breakers, helium or hydrogen would be the most suitable.

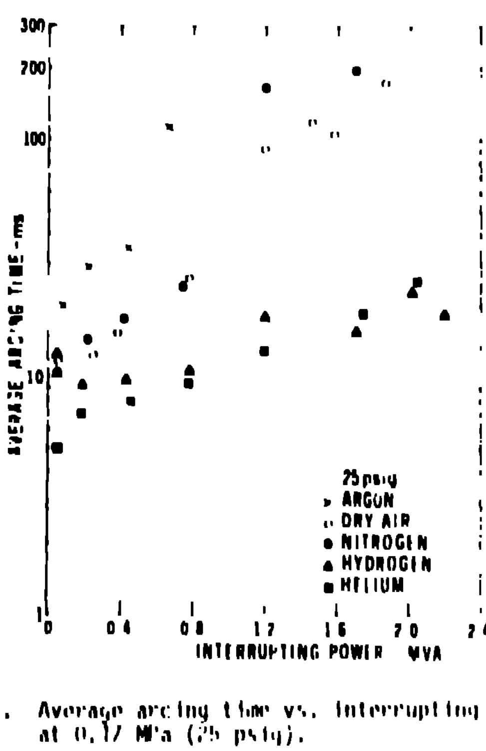


Fig. 1. Average arcing time vs. interrupting power at 0.17 MPa (25 psig).

*Work performed at General Electric Company, Erie, PA.

DC ARC INTERRUPTION IN PRESSURIZED GASES

P. Chowdhuri, Senior Member IEEE
Los Alamos Scientific Laboratory*
Los Alamos, NM 87545

Abstract - The purpose of the study was to investigate the possibility of achieving (1) short interruption time and (2) minimum contact erosion in a dc circuit interrupter. Arc interruption tests were performed on a 100-A, 600-V dc contactor under atmospheres of argon dry air, nitrogen, helium and hydrogen, each at four pressures 0.17, 0.34, 0.52 and 0.69 MPa (25, 50, 75 and 100 psig). It was found that the average arcing time in helium and hydrogen was the shortest, and that in argon the longest for the circuit conditions used. The contact erosion in hydrogen was the worst, and that in argon the best for the contact materials used in the tests. The static pressure in the chamber did not appear to have much effect on the arc interruption phenomenon for the contactor and gas pressures used.

INTRODUCTION

Low-voltage (1000 V and below) dc circuit interruption is of vital importance to many industries, such as transportation, chemical, etc., especially because of the increasing application of power semiconductor devices. The main areas of interest in the technology of low-voltage dc circuit interruption are:

(1) short interruption time
(2) minimum contact erosion

Short interruption time is required to protect the overcurrent-sensitive devices. Contact erosion has always been a serious maintenance problem for dc contactors.

A review of literature showed that most of the previous studies on low-voltage dc arc interruption were made with plain electrodes to understand the basic performance of the various gases. It was thought that the arc runners, the blowout coils and the arc chutes will be essential for low-voltage dc circuit breakers and contactors. Therefore, it would be appropriate to enclose the entire circuit breaker or contactor in atmospheres of various gases to assess its interrupting capability.

REVIEW OF PAST WORK

Suits studied electric arcs between copper electrodes in atmospheres of nitrogen, helium, and hydrogen at 1500 V dc and in the range of 1 to 7 A [1]. The arc voltage increased two times at a pressure of 100 atmospheres of nitrogen from that of one atmosphere, and five times at 1000 atmospheres. The effect of pressure in helium was similar to that in nitrogen. Attempts to obtain measurements in hydrogen showed a striking instability of the hydrogen arc at high pressures. After 12 attempts at 1000 atmospheres of hydrogen, it was found that the arc was extinguishing by virtue of its instability so rapidly that the oscillograms showed only vertical traces where the current decreased to zero and the voltage rose to the full generator value. At this pressure, the arc duration was less than 10 ms.

*Work performed at General Electric Company, Erie, PA.

In his later study, Suits studied the gradient, the arc voltage and the current density in an one-atmosphere hydrogen arc between pure carbon electrodes in the 0-10 A range [2]. Rapid motion pictures of the hydrogen arc at pressures above atmosphere showed violent arc movements originating from convection forces.

Browne found that the ac arc in hydrogen has very high rate of dielectric recovery because of high rate of diffusion of the very light hydrogen ions [3]. It is better than air, oxygen, helium and carbon dioxide. For instance, at 350 μs after current zero (600 A, 60 Hz), the dielectric strength of hydrogen is 500 V/cm; of air is 120 V/cm; of oxygen is 190 V/cm; of helium is 200 V/cm; and of carbon dioxide is 230 V/cm.

Von Engel compared the field intensity of arc voltages in different gases [4]. He found that at 100 A, the field intensity in hydrogen is about 20 times higher than that in air. Next to hydrogen comes water vapor.

To determine the effect of water vapor on arc characteristics, arcs with direct currents in the range from 20 to 200 A were studied by Benner and Jones at atmospheric pressure in air containing water vapor in controlled quantities [5]. The water vapor content of the air was varied from 0.15 to 100 per cent by volume which corresponds to conditions from extremely dry air to saturated steam. Iron, copper, tungsten and graphite were used for the arcing electrodes. It was found that the presence of water vapor causes an increase in arc voltage compared to the arc voltage in dry air. This increase is much greater for the electrode materials, iron and copper, than for tungsten and graphite. These voltage increases appear to occur in both the arc column and the electrode drop regions. From an analysis of the results, it appears that the differences between the effects of air and water vapor on the arc derive from the predominant roles of the large specific heats of water vapor and hydrogen and of the great energy transferring properties of hydrogen attributable to its relatively small mass.

Farrall and Cobine made a study to determine the average duration of dc arcs in various gases at slightly higher than atmospheric pressure [6]. These arcs were drawn between 19.1-mm (3/4-inch) copper contacts in a 1-liter vessel with power being supplied from a 125-V dc generator. The gases studied were hydrogen, nitrogen, helium, sulfur hexafluoride, and oxygen. It was found that in the current range studied (about 1 to 45A) arc duration was always statistical and finite, and that, above 5 A, average arc duration increased for these gases in the order listed above. In the case of oxygen and sulfur hexafluoride, arc stability is believed to have been strongly affected by arc reaction products.

Sulfur hexafluoride (SF_6) has proven to be a good interrupting medium for ac arcs [7]. Because of its electronegative nature, SF_6 recovers its dielectric strength very fast after the current in an ac system passes through zero. That is why it is so successful as an interrupting medium in ac circuit breakers. For dc systems, however, the arc voltage drop has to be higher than the system voltage to quench the arc. This is an important criterion in a dc interrupter. Unfortunately, the voltage gradient in an arc in SF_6 is about as low as that in nitrogen [8], [9].

Basically, the interrupting ability of an interrupter is very much dependent upon the ratio of the heat accumulated in the arc space to the rate of heat loss to the arc boundary. This ratio, known as the arc time constant, was proposed by Cassie [10], Mayr [11] and Browne [12] to study the behavior of an arc under various conditions. The lower the magnitude of the arc time constant, the better will be the interrupting ability of the interrupter.

Yoon and Spindle used this tool to study the relative arc-quenching ability of SF_6, air, N_2, CO_2, He, ClO_3F, O_2 and the mixtures of SF_6 and N_2 [13]. Their tests were performed on stable arcs, i.e., with constant arc current and arc length. Copper "cages" were used to stabilize long arcs. These cages were made up of insulated flat copper rings with various inside diameters and ring spacings.

For a 1-A vertical arc of 25.4-mm (1-inch) length in a 14.3-mm (9/16-inch) cage, the arc time constants of various gases at 0.41 MPa (4 atmospheres) pressure were as follows:

SF_6	:	2 μs
He	:	8.5 μs
Air	:	115 μs
N_2	:	435 μs

For a 6-A vertical arc of 76.2-mm (3-inch) length in a 6.4-mm (1/4-inch) cage, the arc time constants of SF_6 and He at 0.41 MPa (4 atmospheres) pressure were as follows:

SF_6	:	9.5 μs
He	:	5.5 μs

Under these conditions, the arc time constant of He was lower than that of SF_6 up to 0.61 MPa (6 atmospheres) of pressure. It was found that the arc time constant increases with increase in cage diameter and current.

The authors conclude that SF_6 is about 100 times better in ac interrupting ability than air. However, Browne showed that the arc time constant for air was only 5 times greater than that of SF_6 [14]. It should be pointed out that Browne's data were taken from actual circuit-breaker performance under high-pressure and high-flow conditions whereas the Yoon-Spindle data were taken on stationary gas.

It is evident that considerable disagreement remains concerning the performance of the various gases in arc interruption.

TEST PROCEDURES AND RESULTS

Tests were conducted on a 100-A, 600-V dc contactor with arc chute. The contacts were made of copper with silver contact plates brazed to them, the whole assembly being silver dipped. The total volume of the contactor is about 8495 cm^3 (0.3 ft^3).

The contactor was enclosed inside a 0.15-m^3 (5.4-ft^3) steel cylindrical tank of 686-mm (27-inch) length and 533-mm (21-inch) internal diameter. This pressure tank was manufactured to conform with the ASME Code for Unfired Pressure Vessels. The pressure tank was fitted with a safety valve and a relief valve. The safety valve would open with slow build up of pressure. It would bypass the relief valve and vent to the atmosphere. The relief valve would open with sudden build up of pressure, discharging to the atmosphere through vent ports situated in the valve body. The relief valve was set to open at 5.17 MPa (750 psi), and the safety valve at 4.96 MPa (720 psi). The power and control leads were brought to the contactor through bushings fitted to one end plate of the tank.

The electrical schematic diagram is shown in Fig. 1. The dc machines, the resistive load and the breaker #1 were situated in a building 30.4 m (100 ft) away from the test contactor. The power was brought out of the building via cables to the knife switch, the back-up circuit breaker #2 and the test contactor which were located in a semi-enclosed area outside of the building.

The instrumentation room was situated about 7.6 m (25 ft) away from the pressure tank, the intervening space being filled with old and unused water boxes. The instrumentation room contained the CRO, the control power and the various valves for evacuation and filling the pressure tank with the gases at the desired pressures.

The 38-V dc control power to the test contactor was brought through a contactor. This was done for isolation as a safety precaution. The voltage across the normally open contacts of the contactor was brought to the "EXT" trigger terminal of time base B

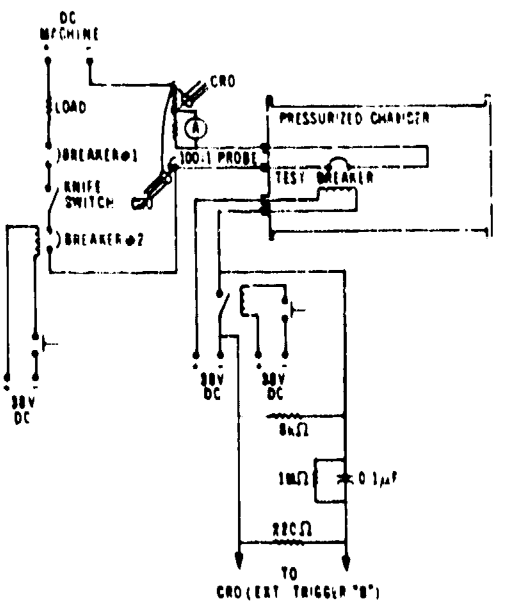


Fig. 1. Schematic of electric circuit for arc interruption.

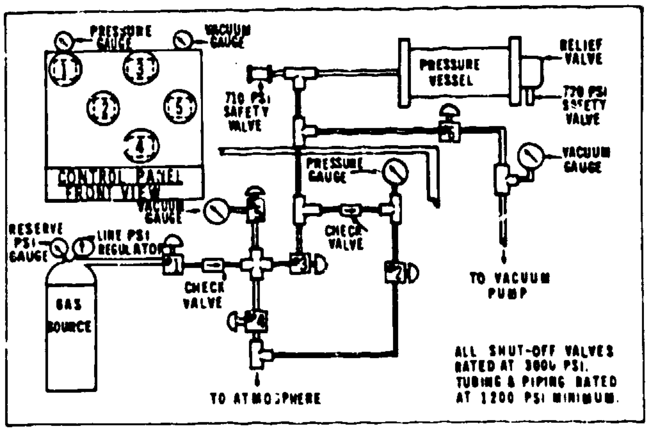


Fig. 2. Schematic of gas circuit for arc interruption.

of a Tektronix 585 CRO through a network (Fig. 1). The CRO was operated at its "A delayed by B" mode of operation. This was done in order to photograph the steady-state voltage (which was zero) across the contacts and the steady-state current through the contacts prior to arcing so that no part of the traces of the arcing current and arcing voltage was lost. The length of the steady-state traces could be varied by varying the delay time control of the CRO. The Tektronix type M plug-in preamplifier was used in the chopped mode to record the arc current and voltage simultaneously. The arc current was measured by a ribbon type shunt and the arc voltage was measured by a 100:1 special voltage probe of 12.2 m (40 ft) length designed in the laboratory.

The sequence of operation was as follows. The pressure tank was evacuated by the vacuum pump to a pressure of 0.58 kPa. The pressure tank was then purged several times with the test gas before being filled with the test gas at the desired pressure. The schematic of the gas lines and their controls is shown in Fig. 2. The breaker #1 and the knife switch in the test area were then closed. The breaker #1 could also be opened, in case of emergency, by opening a foot switch situated in the instrumentation room. The dc machines were then excited to the desired voltage. The actual interruption test was done in the following sequence:

(1) Close test contactor
(2) Close back-up breaker #2
(3) Open test contactor
(4) Open back-up breaker #2

Tests were started at 200 V dc, continued in steps to higher voltages and finished at about 1350 V with a constant resistive load of about 0.8 ohm and about 61 m (200 ft) of connecting cables.

Tests were performed in five gases — argon dry air, nitrogen, helium and hydrogen, each at four pressures — 0.17, 0.34, 0.52 and 0.69 MPa (25, 50, 75 and 100 psig). The purity and dew point of each gas are shown in Table I.

Generally, three interruptions were made at each voltage level. The contacts were changed after each series of test. The main body of the contactor and the arc chute were changed only when the gas was changed. For instance, the same main body and the arc chute of the test contactor were used for all tests in hydrogen, but the contacts were changed after each series of test at a constant pressure.

TABLE I
Specifications of Gases Used

	Argon	Dry Air	Nitrogen	Helium	Hydrogen
Purity %	99.997	-	99.998	99.995	99.5
Dew Point °C	-60	-62.2	-62.2	-60	-60

The test contactors never failed to interrupt the power. The tests were usually terminated when the highest allowable voltage of the dc machines was reached or the arcing time was too long or if the safety valve of the pressure chamber opened because of excessive pressure build up.

The summary of the test results is shown in Figs. 3 and 4. Average arcing times are plotted against interrupting power on semilog papers to facilitate comparison of performance among the five gases. Typical oscillograms of arc current and arc voltage in the five gases at 0.17 MPa (25 psig) and two system voltages are shown in Figs. 5 to 9. The physical conditions of the contacts after each series of tests are shown in Fig. 10.

DISCUSSION

It should be emphasized that all tests were performed with a constant resistive load of 0.82 ohm and the inductance associated with approximately 61 m (200 ft) of connecting cable. The interrupting power was varied by varying the source voltage. This was done because of two reasons. First, it was simpler and faster to vary the interrupting power by varying the voltage. Second, contact sticking problem was encountered when the interrupting power was increased by lowering the load resistance with the source voltage held constant at 600 V. It is believed that it is more difficult to interrupt a given power with higher source voltage than with higher load current, neglecting the contact sticking problem. This belief

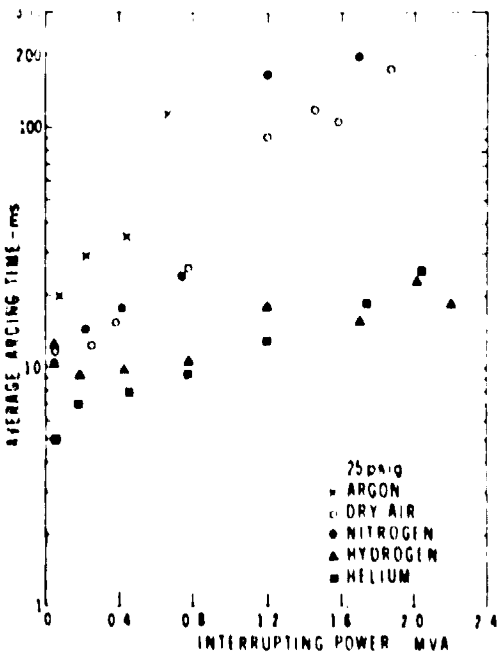


Fig. 3. Average arcing time vs. interrupting power at 0.17 MPa (25 psig).

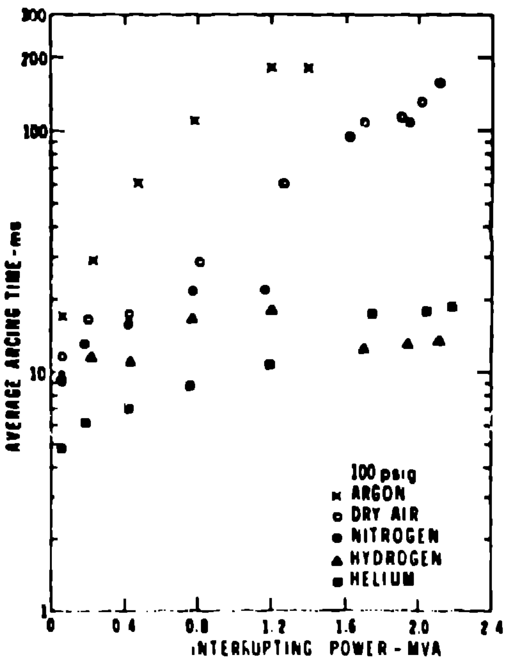


Fig. 4. Average arcing time vs. interruption power at 0.69 MPa (100 psig).

Current trace: 300A/square; 10ms/square
Voltage trace: 200V/square; 10ms/square

Fig. 5. Oscillograms of arc current and arc voltage at 0.17 MPa (25 psig) in argon at 600 Vdc.

is based on the fact that the arc voltage has to be higher than the source voltage for successful interruption in dc systems.

It was found that the contact sticking problem was particularly severe with plain copper contacts. It also appeared that the contact sticking problem was minimized when the moving contact was the positive electrode. All tests described in this paper were performed with copper contacts brazed with silver contact plates and with the moving contact connected to the positive side of the source voltage.

It will be evident from Figs. 3 and 4 that the static gas pressure does not seem to have any significant effect on the arcing time.

Comparing the five gases (Figs. 3 and 4), it was found that the arcing time was the longest in argon. Air and nitrogen are comparable to each other, taking the second longest time to interrupt an arc. Helium and hydrogen take the shortest time to interrupt an arc.

The performance of the various gases can be qualitatively assessed by studying their physical and thermodynamic properties. The arcing time T_a of a dc arc can be expressed as [15]

$$T_a = L\int_I^0 di/(V-Ri-V_a)$$

where V = source voltage,
L = system inductance,
R = system resistance,
I = initial arc current,
i = instantaneous arc current, and
V_a = arc voltage.

The arc voltage V_a must be higher than (V-Ri) for the arc to quench. For the same system conditions, the arcing time will decrease if the arc voltage V_a is rectangular and as high in magnitude as possible without endangering the system insulation [16].

A rectangular arc voltage is never achieved in practice. However, its rise time can be shortened by increasing the contact-opening speed of the interrupter. For the same interrupter, however, the rise time can be significantly reduced, and the magnitude of the arc voltage increased if the gaseous medium has high thermal capacity, thermal conductivity and diffusivity. High thermal capacity of the gas would lower the arc temperature, thus lowering its electrical conductivity and increasing the voltage drop across the arc; high thermal conductivity of the gas would cool down the arc column at a high rate by transferring heat from the arc to the surrounding cool gas according to the relationship [17]

$$\partial H/\partial t = -kA(\partial T/\partial r)$$

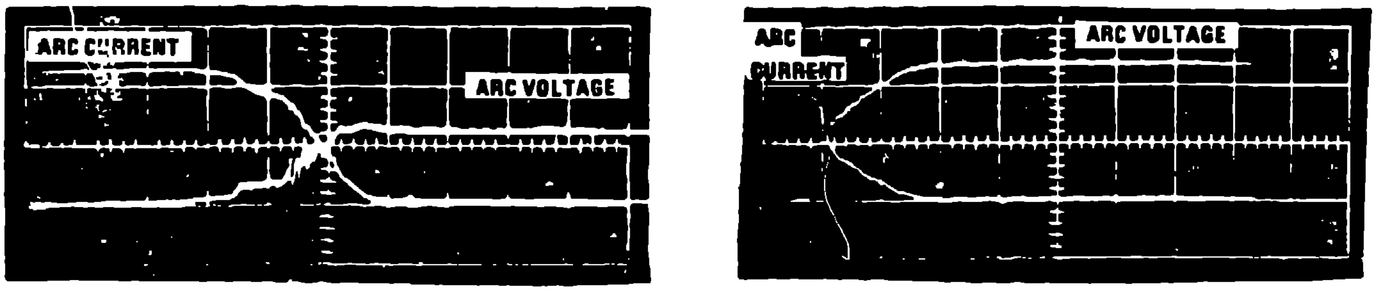
where H = heat flux,
k = thermal conductivity,
A = surface area of the arc column,
T = temperature, and
r = radial distance from the arc.

High diffusivity would deionize the arc column by transporting the ions to the surrounding enclosure according to the relationship 17

$$\partial n/\partial t = q + D\nabla^2 n$$

where n = number of ions in a unit volume,
q = number of ions generated in a unit volume/second,
D = coefficient of diffusion.

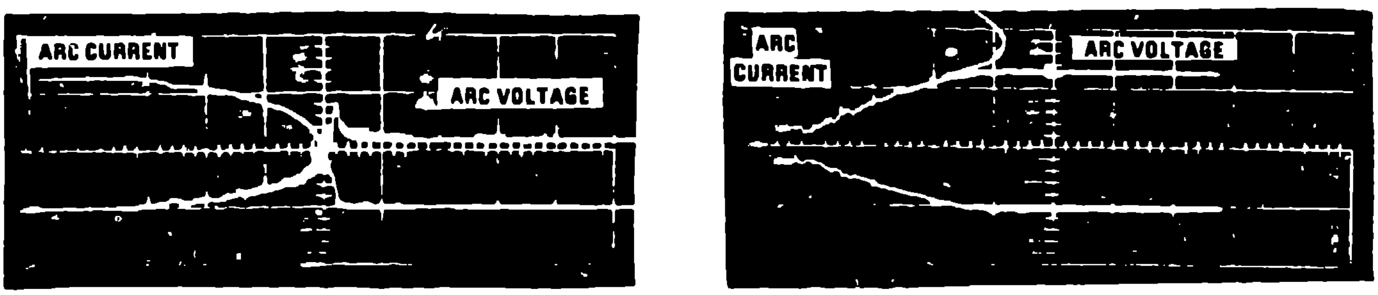
The ability to withstand the system transient recovery voltage after arc quenching is also an important performance criterion for an interrupter. The post-arc recovery of an interrupter is achieved in two stages: thermal recovery and dielectric recovery. Immediately after current zero the arc path would have enough electrical conductivity that would generate ohmic heating by the resulting transient recovery voltage. Excessive heating would cause a restrike. However, if the ions are dispersed by cooling and diffusion, the thermal recovery of the arc path will be complete. High thermal conductivity and diffusivity of the gas would play an important role for successful thermal recovery. Dielectric recovery starts after the thermal recovery is complete, when no ohmic heating of the arc path takes place. The dielectric strength of a gas increases as its temperature decreases. The interrupter will have a successful dielectric recovery if the rate of rise of the transient recovery voltage and the rate of dielectric recovery are such that the instantaneous value of the transient recovery voltage is never



(a) At 600 Vdc
Current trace: 300A/square; 5ms square
Voltage trace: 500V/square; 5ms square

(b) At 1200 Vdc
Current trace: 750A/square; 50ms/square
Voltage trace: 500V/square; 50ms/square

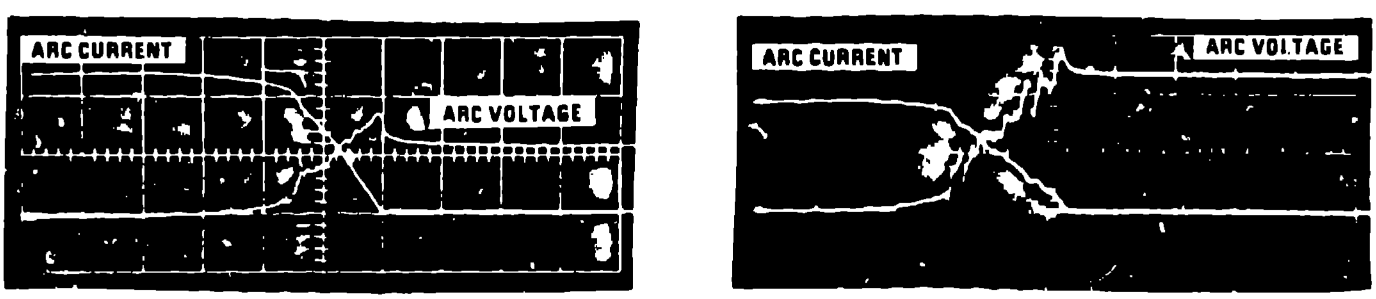
Fig. 6. Oscillograms of arc currents and arc voltages at 0.17 MPa (25 psig) in dry air.



(a) At 600 Vdc
Current trace: 300A/square; 5ms/square
Voltage trace: 500V/square; 5ms/square

(b) At 1200 Vdc
Current trace: 750A/square; 50ms/square
Voltage trace: 500V/square; 50ms/square

Fig. 7. Oscillograms of arc currents and arc voltages at 0.17 MPa (25 psig) in nitrogen.



(a) At 600 Vdc
Current trace: 300A/square; 2ms/square
Voltage trace: 500V/square; 2ms/square

(b) At 1200 Vdc
Current trace: 750A/square; 5ms/square
Voltage trace: 500V/square; 5ms/square

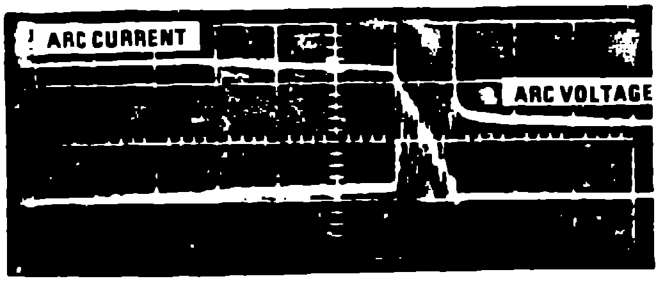
Fig. 8. Oscillograms of arc currents and arc voltages at 0.17 MPa (25 psig) in helium.

higher than the instantaneous dielectric strength of the gas at the arc path. This requires a gas of high dielectric strength.

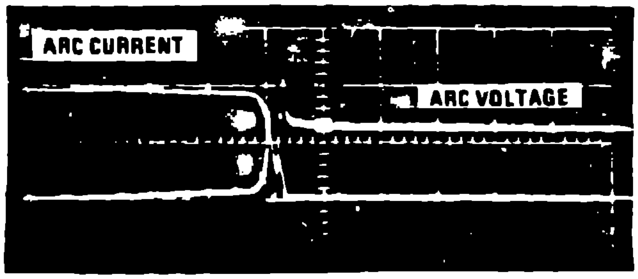
Table II shows the pertinent physical and thermodynamic properties of the gases. Data on the diffusivity are not readily available. Therefore, the data on mobility are given, because mobility is directly proportional to the coefficient of diffusion by the Einstein relation. The temperature and pressure conditions of this Table do not represent those of an actual interrupter. However, the data show the relative standing of the gases.

The data in Table II corroborate our experimental evidence that the arc duration in argon is the longest, and that in helium and hydrogen the shortest. None of the gases has high dielectric strength. However, the high cooling rate of helium and hydrogen would provide high post-arc recovery rate which is a critical performance criterion for circuit interruption.

Only visual inspection was made of the physical conditions of the contacts, arc chute and the main body of the contractor. The contacts are shown in Fig. 10. It will be noticed from Fig. 10 that the silver-tipped contacts are eroded the least in argon. Hydrogen eroded the contacts the most. Interruption in hydrogen produced heavy blisters on the contact tips and charred the contact surface black. Dry air and nitrogen are comparable to each



(a) At 600 Vdc
Current trace: 300A/square; 2ms/square
Voltage trace: 500V/square; 2ms/square



(b) At 1200 Vdc
Current trace: 750A/square; 5ms/square
Voltage trace: 1000V/square; 5ms/square

Fig. 9. Oscillograms of arc currents and arc voltages at 0.17 MPa (25 psig) in hydrogen.

other for contact erosion, and are the second worst media. Helium is the second best medium for contact erosion. For contact erosion, the gases are, in order of preference: Argon, helium, air/nitrogen and hydrogen. The arc chute remained fairly undamaged in all five gases. However, the main body of the contactor was damaged during interruption in argon and air. In nitrogen at 0.17 MPa, part of the arc runner broke loose because of melting caused presumably by a stationary arc. The molten metal dropped on the bolts of the contacts, thus making it impossible to disassemble.

It should be observed from the oscillograms of Figs. 5 to 9 that arc interruption is completed in two stages. During the first stage, the arc voltage increases slowly with the accompanying slow decrease of the arc current. During the second stage, the arc voltage increases rapidly accompained by a rapid decrease of the arc current. The first stage occurs during the opening of the contacts when the arc is still stationary. During the second stage, the arc is blown to the arc runners by the blow-out coil and is, therefore, rapidly increasing in length. The duration of the first stage in hydrogen seems to be longer than that in the other four gases. The excessive contact erosion in hydrogen may have been caused in part by lingering stationary arc.

Voltage spikes were observed at the instant of interruption in nitrogen, hydrogen and helium, the highest voltage spikes being generated by hydrogen. Hydrogen produced voltage spikes also during arcing. An arc in hydrogen will thus act as a source of broadband electrical noise. Negative current spikes were also observed at the instant of interruption in hydrogen, especially at lower source voltage levels.

TABLE II

Pertinent Physical and Thermodynamic Properties of Gases at 273K and 760 mm Hg

	Ar	N_2	He	H_2
Specific heat capacity C_p (J/g-K) [18] - [20]	0.52	1.04	5.19	14.19
Thermal conductivity (mW/m-K) [19] - [21]	18.6	23.0	142.0	162.0
Mobility of positive ions (cm/s/V/cm) [17]	1.37	1.27	5.09	5.9
Voltage gradient in arc at I = 20 A (V/cm) [17]	6	15	20	55
Minimum sparking voltage (V) [17]	137	251	156	273

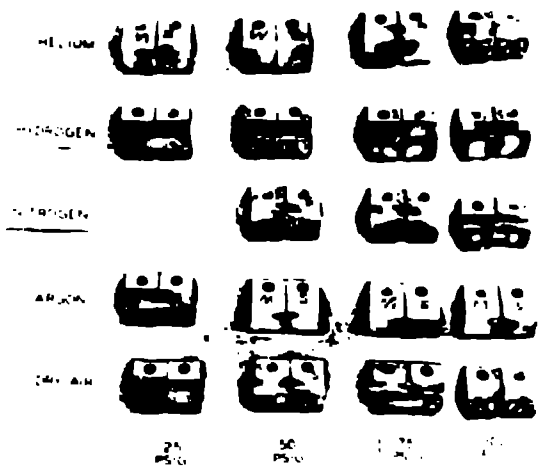


Fig. 10. Photograph of contacts after each series of tests.

The inferior performance of argon as a medium of arc interruption was previously shown by Farrall and Cobine at a much lower power level [6]. Our results confirm this observation at a higher power level. However, it was surprising to observe that contact erosion was the least with argon in spite of the longest arc duration. Chemical reaction of the surrounding gas with the contact material is partly responsible for contact erosion. Argon, being one of the most inert gases, would have the least reaction with the contact materials. Perhaps this is the reason for the least contact erosion in argon.

Although Farrall and Cobine [6] showed that helium is inferior to nitrogen for arc interruption above 5 A, our test results place helium in the same class as hydrogen. This is in line with the observation of Yoon and Spindle [11] who found that the arc time constant for helium is much shorter than that of either air or nitrogen.

Yoon and Spindle [13] found that the arc time constant in nitrogen is several times larger than that in air, although Farrall and Cobine [6] found the average arc duration in nitorgen comparable with that in hydroger above 20 A. Our test results show that air and nitrogen are comparable as arc interrupting media.

The performance of hydrogen did not quite come up to our expectations. Although our tests were not carried out up to failure, comparing the arcing times it is estimated that the interrupting ability of hydrogen would not be better than ten times that of air under our experimental conditions. It is anticipated that the influence of the arc runners and the arc chute might have masked the influence of the surrounding gas to some degree.

The long delay of the hydrogen arc in being transferred to the arc runners has certainly contributed to the limitation. Because of incompatibility between hydrogen and silver-tipped contacts, blisters appeared at the origin of the arc on the contacts. This produced "sticking" of the arc at its roots. It is anticipated that this required larger force to move the arc on to the arc runner; hence, the delay.

CONCLUSIONS

(1) For the test conditions:

- (a) the average arcing times in helium and hydrogen are the shortest and that in argon the longest;
- (b) contact erosion in hydrogen is the worst and that in argon the least; and
- (c) the static pressure in the chamber does not appear to have much effect on the arc interruption phenomenon.

(2) For relatively low-power and slow-speed interruptions, such as contactors, argon would be the best medium because it produces the least contact erosion. For high-power and high-speed interruptions, such as circuit breakers, helium or hydrogen would be the most suitable.

ACKNOWLEDGEMENT

This work was carried out at the Transportation Systems Division of the General Electric Company, Erie, PA. The author gratefully acknowledges the assistance of N. Galich in obtaining the experimental data, and the support, advice, and encouragement of H. W. Gayek, R. C. Leever, and M. Simon, all of the General Electric Company, Erie, PA.

REFERENCES

[1] C. G. Suits, "Measurement of Some Arc Characteristics at 1000 Atmospheric Pressures," Journal of Applied Physics, vol. 10, pp. 203-206, 1939.

[2] C. G. Suits, "Some Properties of Hydrogen Arc," ibid, vol. 10, pp 648-650, 1939.

[3] T. E. Browne, Jr., "Dielectric Recovery of a Arcs in Turbulent Gases," Physics, vol. 5, pp. 103-113, 1934.

[4] A. Von Engel, Ionized Gases. New York: Oxford at the Clarendon Press, 1955.

[5] R. H. Benner, II and T. B. Jones, "Influence of Atmospheric Water Vapor on High-Current dc Arcs," AIEE Transactions, vol. 75, pt. II, pp. 162-166, July 1956.

[6] G. A. Farrall and J. D. Cobine, "Stability of Arcs in Gases," Journal of Applied Physics, vol. 36, no. 1, pp. 53-56, January 1965.

[7] H. J. Lingal, A. P. Strom and T. E. Browne, Jr., "An Investigation of the Arc-Quenching Behavior of Sulfur Hexafluoride," AIEE Transactions, vol. 72, pt. III, pp. 242-246, April 1953.

[8] T. Sakakibara, Y. Kito and I. Miyachi, "Voltage Gradient of Pressurized SF_6 Gas Arc in Very Low Current Range," Proc. Third International Conference on Gas Discharges, IEE Conference Publication No. 118, London, England, pp. 24-27, 1974.

[9] I. Miyachi and H. Naganawa, "Spiral Arc in SF_6 Facilitating dc Interruption," ibid, pp. 521-524.

[10] A. M. Cassie, "Arc Rupture and Circuit Severity: A New Theory," CIGRE, Paper No. 102, 1939.

[11] O. Mayr, "Beitrag zur Theorie der statischen und dynamischen Lightbogens," Archiv fuer Elektrotechnik, vol. 37, pp. 588-608, 19[illegible]

[12] T. E. Browne, Jr., "A Study of Arc Behavior near Current Zero by Means of Mathematical Models," AIEE Transactions, vol. 67, pt. I, pp. 141-153, 1948.

[13] K. H. Yoon and H. E. Spindle, "A Study of the Dynamic Response of Arcs in Various Gases," ibid, vol. 77, pt. III, pp. 1634-1641, 1959.

[14] T. E. Browne, Jr., "An Approach to Mathematical Analysis of Arc Extinction in Circuit Breakers," ibid, vol. 77, pt. III, pp. 1508-1517, 1958.

[15] R. Ruedenberg, Transient Performance of Electric Power Systems. New York: McGraw-Hill, 1950.

[16] E. W. Boehne and [illegible] Jang, "Performance Criteria of dc Interrupters," AIEE Transactions, vol. 66, pp. 117[illegible]-1180, 1947.

[17] J. D. Cobine, Gaseous Conductors. New York: Dover, 1958.

[18] S. Angus and B. Armstrong, Eds., International Thermodynamic Tables of the Fluid State, Argon, 1971. London: Butterworths, 19[illegible].

[19] R. D. McCarty, Thermophysical Properties of Helium-4 from [illegible] to [illegible] with Pressures [illegible] Atmospheres. NBS Technical Note [illegible]. Boulder, National Bureau of Standards, 19[illegible].

[20] R. D. McCarty, Hydrogen. Its Technology and Implications, Hydrogen Properties, [illegible]. Cleveland: CRC Press, 19[illegible].

[21] N. V. Tsederberg, Thermal Conductivity of Gases and Liquids. Cambridge: MIT Press, 19[illegible].